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REVIEW OF THE DEVELOPMENT OF SUSPENSION BRIDGES AND BRIDGES WITH INCLINED CABLES WITH A FOCUS ON NEW TECHNOLOGIES AND THE OAKLAND BAY AND YAVUZ SULTAN SELIM BRIDGES

Abstract

Bridges are among the oldest structures that humans have built throughout history. Over time, along with technological advancements, various structural systems for bridges have been discovered. This overview paper analyzes suspension bridges and bridges with inclined cables, delving deeper into the issues and construction technology of two specific bridges: the Oakland Bay Bridge in San Francisco and the Sultan Selim I Bridge in Istanbul. The paper showcases innovations adopted from previous experiences that distinguish these structures in their class.

Keywords: suspension bridge, cable-stayed bridge, Oakland Bay Bridge, Yavuz Sultan Selim Bridge

ПРЕГЛЕД РАЗВОЈА ВИСЕЋИХ МОСТОВА И МОСТОВА СА КОСИМ КАБЛОВИМА СА АКЦЕНТОМ НА НОВЕ ТЕХНОЛОГИЈЕ И МОСТОВЕ ОУКЛЕНД БЕЈ И СУЛТАН СЕЛИМ I

Сажетак

Мостови су једни од најстаријих објеката које су људи градили кроз историју. Током времена, заједно са напредовањем технологије, откривени су различити конструктивни системи за мостове. Овај прегледни рад анализира висеће мостове и мостове са косим кабловима, дубље улазећи у проблеме и технологију градње два конкретна моста: Оукленд Беј моста у Сан Франциску и Султан Селим I моста у Истанбулу. Рад представља иновације прихваћене из претходних искустава које ове објекте истичу у својој класи.

Кључне ријечи: висећи мост, мост са косим кабловима, Оукленд Беј мост, Султан Селим I мост

1. INTRODUCTION

The main purpose of a bridge as a structure is to transfer the traffic load over an opening or a discontinuity in the terrain. Different types of bridges are built to withstand the load from pedestrians, motor vehicles, various types of lines, trains or a combination of the above. Bridging is done over highways, rivers, valleys or any other physical obstacle. The need to transfer the load through the specified openings defines the function of the bridge. The design of the bridge structure can only be started after defining the role of the bridge, therefore the bridge construction process is not started by the engineer designing the bridge. It is necessary that the bridge meets the requirements in terms of: safety, functionality, economy and meets all aesthetic requirements. The safety of the bridge is uncompromising, and therefore the bridge should remain safe under all types of loads for which it was designed.

Suspension bridges have a very wide area of use, bridging large spans, and are one of the oldest and most common types of bridges. After the discovery of steel with high mechanical performance, modern suspension bridges began to be developed and built. Two significant forms, load-bearing systems and materials, have made suspension bridges span greater spans than any other type of bridge, including girder, arch and truss bridges.

Also, they can bridge larger spans, while respecting efficiency aspect. Bridge girders of suspension bridges are supported by main cables hanging from pylons, [1].

Cable-stayed bridges belong to the newer types of bridges, and the technology of constructing cable-stayed bridges has become even more important with the increase in the span of the bridges themselves and the complexity of the bridge structures. A cable-stayed bridge consists of three main components, which include pylons, cables and the bridge girder. The constructive system of cable-stayed bridges consists of four components: foundation, pylon, bridge girder and cables. The construction of the foundation can be on piles, crates, caissons, and is similar to other types of bridges [2]. The girder of a cable-stayed bridge is usually a prestressed concrete rigid beam, steel beam, composite beam, or steel truss. Similar to the construction of girder bridges, the bridge girders of the cable-stayed bridge can be made according to the system of in situ formation, pushing, assembly using a crane, etc.

2. TYPES OF BRIDGES

All bridges can be grouped into four basic types: girder bridges, arch bridges, cable-stayed bridges and suspension bridges. There are also specific variations, which will be described in more detail below. Common sense tells us that girder bridges and arch bridges are suitable for short to medium spans, while cable-stayed bridges are suitable for medium to long spans and suspension bridges for very long spans. Based on these assumptions, experience suggests rules to assign each span the appropriate type of bridge. For example, in the 1960s, a reasonable maximum span for a cable-stayed bridge was 450 meters, while for a girder bridge it was approximately 250 meters. These assumptions did not last long, since cable-stayed bridges with spans over 1000 meters were built. When a part of the element does not participate in carrying the load or is not used to the end, more material is needed to carry the same load, therefore the self-load increases, which is a major disadvantage of bridges, especially bridges with large spans. Currently, the world span records for each of these types of bridges are: 330 meters Shibanpo Bridge in China [2], which has the largest girder span; 552 meter Chaotianmen Bridge in China, which has the largest arch span; 1104 meters Vladivostok bridge in Russia, which has the largest span of a cable-stayed bridge; 1991 meter Akashi Kaikyo bridge in Japan, which has the largest suspension span.

3. CABLE-STAYED BRIDGE

The rapid development of cable-stayed bridges begins with the use of high-quality cable steel. The beginnings of modern bridges of this structural system date back to the mid-1960s, and the trend of building these bridges continued and accelerated in the 1960s, 1970s and 1980s, so that today there are bridges under construction with spans of more than 500 meters [4].

The basic structural form of a cable-stayed bridge consists of radially formed cables that form a triangular shape with pylons and stiffening beams, Fig.1. The axial compressive force in the girder and pylons are in balance with the tension forces from the cables. Since the loads transferred are mostly axial forces, and not bending moments, conditions are created for the construction of more effective and economical structures. Cable-stayed bridges are usually self-anchored, which makes them a good solution in locations where the soil quality conditions are not good, as a result of which anchoring in the soil, as is the case with most suspension bridges, would be unjustified - expensive. In a cable-stayed bridge, the axial force in the girder is approximately zero at mid-span and increases to a maximum at the tower [1]. Therefore, if we increase the cross-section of the beam with an increase in axial force, the permissible axial force can be increased, and thus the span of the bridge. In this way, theoretically, the maximum range can be increased to over 10,000 meters. Considering the mutual position of the inclined cables in the longitudinal direction of the bridge, the following characteristic cases are distinguished: Bridges with radial arrangement of cables; Bridges with mutually parallel cables - "harp" layout; Bridges where the cables are connected to the pylon at different levels along the pylon, and the cables are not parallel to each other - "fan" arrangement; "Star" arrangement, where two cables each depart from the pylon at different levels, and intersect at one point on the bridge girder.

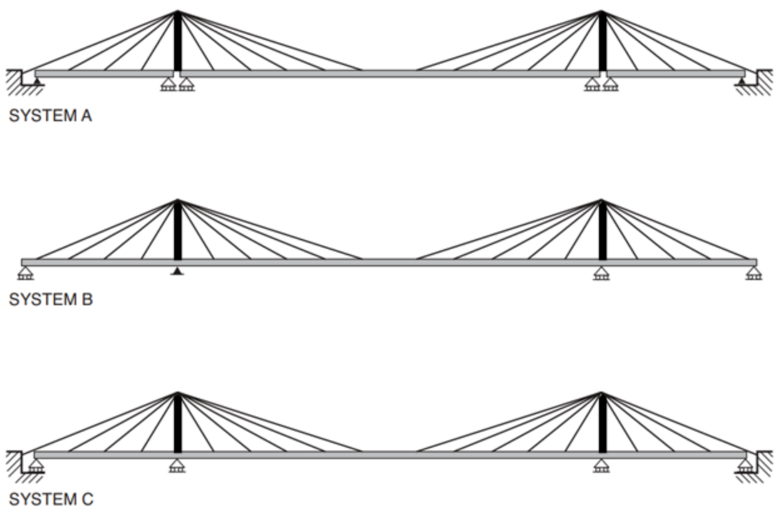

Figure 1. Various support systems for cable-stayed bridges.

3.2. MAXIMUM SPANS OF BRIDGES WITH INCLINED CABLES

Cable-stayed bridges became very popular after the construction of the first bridge of this type, Table 1. The Strömsund Bridge in Sweden, was completed in 1955. Due to the versatility of cable-stayed bridges, this type has been adopted for various spans; from pedestrian bridges shorter than 50 meters, up to spans of more than 1000 meters, which carry the traffic load.

Table 1. Table 2 Oldest cable-stayed bridges

No	Bridge	Head engineer/company	Country	Year of completion	Longest span [m]
1.	Strömsund	Demag	Sweden	1955.	182,6
2.	Theodor Heuss	Friedrich Tamms	Germany	1957.	260
3.	Severins	Gerd Lohmer	Germany	1961.	302
4.	Knie	Fritz Leonhardt	Germany	1969.	319
5.	Duisburg-Neuenkamp	Keipke Architekten	Germany	1970.	350
6.	Saint Nazaire	CFEM; SGE	France	1977.	404
7.	Barrios de Luna	Carlos Fernández Casado	Spain	1983.	440
8.	Alex Fraser	Buckland & Taylor; CBA Engineering	Canada	1986.	465
9.	Ikuchi	Honshu Shikoku Bridge Authority	Japan	1991.	490
10.	Skarnsundet	Aker ASA	Norway	1991.	530

The Ada bridge is certainly one of the more famous bridges in our region, Fig. 2. Built with a cable-stayed bridge system, the bridge spans the Sava River and consists of one 207-meter-high pylon and two asymmetric spans. The bridge is 920 meters long, with a main span of 375 meters. The road is 45 meters wide. It's designers are engineer Viktor Markelj and architect Peter Gabrielcic, while the executing companies were: "Porr Technobau and Umwelt Aktiengesellschaft" (Austria), "SCT" (Slovenia) and "DSD" (Germany).

Figure 2. Ada Bridge, Belgrade.

Millau Viaduct is located in France and is the highest viaduct in the world, Fig. 3. It is 2460 meters long, consisting of six spans of 342 meters and two spans of 204 meters [4]. It was built as a cable-stayed bridge. The height of the bridge pylon is 343 meters. It's designers are engineer Michel Virlogeux and architect Norman Foster, while the executing companies were: "CEVM" (France), "PAECH Construction Enerprise" (Poland), "Dragados" (Spain), "Société di Viaduc de Millau" (France) and "Générale Routiére" (France).

Figure 3. Millau Viaduct.

4. SUSPENSION BRIDGES

The beginnings of suspension bridges date back a long time. Primitive suspension bridges or simple bridging elements were the forerunners of today's suspension bridges. These bridges were built with iron chains more than 2000 years ago in China, and similar records exist in India. Iron suspension bridges, which are supposed to have been designed in the Orient, appeared in Europe in the 16th century and were developed in the 18th century. Modern suspension bridges date from the 18th century, and are linked to the development of bridge structures and the realization of maximum production capacities. The Jacob's Creek Bridge was built in the USA in 1801, and had an average span of 21.3 meters [1]. The bridge was special in that a beam was used to strengthen the grid, which gave additional rigidity to the bridge, which enabled the load to be transferred through the cables, thus preventing large deformations. Clifton Bridge, with a middle span of 214 meters, is the oldest suspension bridge for vehicle traffic currently in use, the construction of which began in 1831 and ended in 1864 in the United Kingdom, using iron chains like cables. Suspension bridges can be rationally applied for spans of 250-1500 meters, and there are project solutions for much larger spans, as well as bridges of smaller spans. The main elements of the supporting structure of the suspension bridge are:

- The load-bearing cables, which for modern load-bearing bridges are mainly made of closed spiral ropes.
- Stiffening beam, solid sheer or lattice steel girder of constant height.

The erection procedure of earth anchored suspension bridges can be divided into six stages:

- Stage 1 Construction of the main piers, pylons, and anchor blocks.
- Stage 2 Erection of the main cables.
- Stage 3 Start of erection of the deck from the center of the main span. When the weight of the deck is added stepwise to the main cable, large displacements and changes of curvature occur, and the joints between the segments of the deck are therefore intially left open to avoid excessive bending of the girder sections.
- Stage 4 Erection of the deck in the side spans to reduce the horizontal displacements of the pylon tops.
- Stage 5 Erection of the closing pieces in the deck at the pylons.
- Stage 6 Closing of all deck joints. Actually, the closing of these joints will often start already during stages 4 and 5, as soon as adjoining segments become lined up. Fig. 4. a)

Another erection procedure to be found within suspension bridges exists. The sequence of adding the deck segments is the opposite of that mentioned earlier Fig. 4. b)

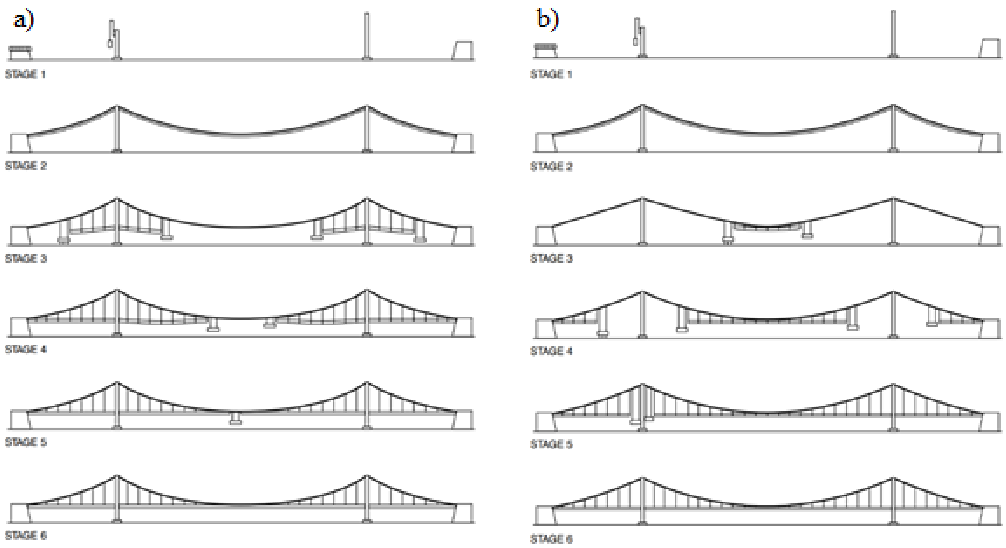

Figure 4. Phases of construction of suspension bridges.

The shape of the cross-section primarily depends on: the span, the width of the bridge and the spacing of the hangers. Pylons serve as a support for stiffening beams and supporting cables on the bend - saddle, and can be made of steel or lattice portals made of reinforced concrete. Hangers are made of round steel or steel rope and have a stiffening beam suspended from a supporting cable. Anchor blocks are made of concrete into which the supporting cables are anchored, and they can be located in the ground or in the stiffening beam. Couplings against the wind are omitted in certain cases of beams for stiffening in the horizontal plane.

4.2. MAXIMUM SPANS OF SUSPENSION BRIDGES

Development of modern materials has led to a significant increase in the possible spans of bridges, Table 2, and by the end of the twentieth century, some of the largest spans listed in the table were built.

Table 2. Table 3 Maximum spans of suspension bridges

No	Bridge	Country	Head engineer/company	Year of Completion	Longest Span [m]	Bridge Type
1	Akashi Kaikyo	Japan	Satoshi Kashima	1998.	960+1991+960	3 Spans, 2 Hinges
2	Zhoushan Xihoumen	China	China Communications Construction Company	2008.	578+1650+(485)	Continual
3	Great Belt East	Denmark	COWI; Ramboll; Dissing+Weitling	1998.	535+1624+535	Single Span
4	[1] Runyang Yangtze River	China	Jiangsu Province Communications Planning and Design Institute	2005.	(470)+1490+(470)	3 Spans, 2 Hinges
5	Humber	UK	Freeman, Fox and Partners	1981.	280+1410+530	3 Spans, 2 Hinges
6	Jiangyin Yangtze River	China	Cleveland Bridge and Engineering Co. Ltd.	1999.	(336,5)+1385+(309,4)	Single Span
7	Tsing Ma	China	Mott MacDonald	1997.	355,5+1377+(300)	Continual
8	Verrazano Narrows	USA	Othmar Ammann; Leopold Just	1964.	370,3+1298,5+370,3	3 Spans, 2 Hinges
9	Golden Gate	USA	Joseph B. Strauss	1937.	342,9+1280,2+342,9	3 Spans, 2 Hinges
10	Yangluo Yangtze River	China	China Communications Construction Company	2007.	(250)+1280+(440)	Single Span

4.3. COMBINATION OF SUSPENSION BRIDGES AND CABLE-STAYED BRIDGES

Previous general reflections show that for suspension bridges the maximum span is limited by the permissible tensile stress in the cables, while for cable-stayed bridges the limiting factor is the compressive stress in the beam. It follows that the span can be increased if a combination of these two types of bridges is made. Another way to increase the span of a cable-stayed bridge was found by anchoring some of the cables into the ground.

The purpose of determining the maximum possible range is to ensure that, in a technological sense, the range does not represent a problem in the conceptual solution. The cost of the bridge increases rapidly with the increase of the span of the bridge, and one must be careful when choosing spans that are larger than required. This also suggests that the pursuit of a world span record is not necessarily a wise or practical endeavor. It is actually a waste of money if the spread is unnecessarily higher than required.

4.4. SELF-ANCHORED BRIDGES AND GROUND-ANCHORED BRIDGES

A self-anchored bridge is a bridge that does not need additional horizontal anchorage, as is the case with cable-stayed bridges or girder bridges. The main cables of a suspension bridge must be anchored in some other way at both ends to resist the horizontal forces from the cables. There are two ways to solve the problem of horizontal forces: either cable can be anchored to the ground or the cables can be anchored to the beam at both ends. Another way is to form a self-anchored suspension bridge, Fig. 5.

Since the cables of a self-anchored suspension bridge are anchored into the bridge girder at both ends, and since the force in the cables is transferred to the bridge girder, it must be constructed before the cables are placed, which makes the construction of the bridge difficult. The cables also introduce enormous axial forces into the bridge girder, which, depending on the span, cause the need to strengthen the bridge girder in cross-section, which further increases the cost price. This explains why self-anchored bridges are usually of smaller span.

Figure 5. Types of cable anchoring.

The 385-meter span of the San Francisco Oakland Bay Bridge in California, on its eastern span, holds the world record for the largest self-supporting span, which was designed by Donald MacDonald Architects and built by American Bridge Co. and Fluor Enterprises. This span is relatively small compared to the largest span of an anchored bridge in the world – the Akashi Kaikyo Bridge in Japan, Fig. 6, with a span of 1,991 meters. There are situations when self-anchored bridges are the right choice, especially when soil conditions make ground anchoring very difficult.

This is precisely the reason why the Oakland Bay Bridge was built as a self-anchored suspension bridge - although on one side it had a good foundation in the form of solid rock, the other end required a foundation in more than 100 meters of mud, which made ground anchoring practically impossible.

Figure 6. Akashi Kaikyo Bridge.

The focus now shifts to two memorable bridges, Oakland Bay Bridge and Yavuz Sultan Selim Bridge. These bridges are chosen on account of the marvelous ingenuity. Oakland Bay Bridge holds the record for the longest self-anchored span. Yavuz Sultan Selim Bridge has a unique mechanism for reduction of the longitudinal displacement of the platform and bending of the pylon under heavy rail traffic, as well as a defense mechanism for seismic activities.

5. SAN FRANCISCO-OAKLAND BAY BRIDGE

The first design for the San Francisco-Oakland Bay Bridge was made in 1914, approximately twenty years before the original bridge was completed. The original construction began in 1933, while the bridge was put into use in 1936.

Bridge designers have known for more than 30 years that a major earthquake on either of the two nearby faults (San Andreas and Hayward) could destroy the bridge's main span, Fig. 7. Little was done to solve this problem until the Loma Prieta earthquake in 1989. The earthquake was of magnitude 6.9 and while the epicenter was far from the bridge, a 15-meter section of the upper bridge structure of the eastern viaduct of the bridge collapsed onto the lower floor, which indirectly resulted in one death at the site of the collapse.

Figure 7. The appearance of the old East Crossing.

The design selection process for the new bridge marked a fundamental shift in state and regional decision-making in California on one of the largest and most expensive transportation infrastructure projects in the state. The selection of solutions from the proposed variants began in 1997. However, the state of California halted construction of the $6 billion bridge in 2004 when it faced a $3 billion cost overrun.

Construction of the San Francisco-Oakland Bay Self-Anchored Suspension Span began in 2006, and the bridge officially opened in February 2014. The San Francisco-Oakland Bay Bridge East Span Replacement was a construction project that replaced a seismically failing section of the bridge with a new self-anchored suspension bridge. and viaduct. The viaduct connects the suspension part of the bridge with the Oakland waterfront. Considering that the viaduct crosses the shallower part of the bay, the foundations were made within piles. In the middle of 2009, the final connection of the part of the viaduct with the ground level at the eastern end was completed and the pedestrian path of the completed section was connected. The works were completed 34 hours ahead of schedule, and the bridge was opened to traffic on February 19, 2014.

5.2. GENERAL DESIGN OF THE OLD BRIDGE

The old San Francisco-Oakland Bay Bridge opened to traffic in 1936, it’s designers are Ralph Modjeski and Charles Purcell and it was built by the American Bridge Company. It connects San Francisco and Oakland and is the busiest transportation link in Northern California. The bridge, in fact, is formed of several parts with distinctly different structural systems and solutions, connected together to form a single unit of about 13.7 kilometers across the bay, almost 7.1 kilometers across the water. The complete bridge structure was formed as follows: West Crossing: Nearly 3.1 kilometers from San Francisco to Yerba Buena Island, including a two-pylon suspension bridge with a center span of over 704 meters, A 549-meter segment with a tunnel and a short concrete viaduct, East Crossing: More than 3,400 meters from Jerba Buena Island to Oakland, consisting of several different steel truss systems: four smaller 88-meter spans at Jerba Buena, followed by a 738-meter cantilever structure, and then five truss spans at 155 meters, fourteen spans on the bridge structure of 88 meters each, and the rest on simple steel structures on land.

5.3. SEISMIC IMPACT ON THE BRIDGE STRUCTURE

For the safety assessment event, the bridge was designed with an appropriate return period of 1000 to 2000 years. Movements since the 1980s corresponded to a magnitude 8 event on the San Andreas fault approximately 15 kilometers from the end of the West Pass. Soil properties were based on boreholes and soil testing for each pier location, East Pass geologic information, and previously published data. Appropriate non-linear foundation springs were developed for these soil layers, through which the movement was directed. Later, seismic improvements were made to the western crossing in a five-year project that began in 1999. Improvements included massive rollers placed between the roadway and the bridge girders and 96 new viscous dampers inserted at critical points to allow movement. The bridge's twin spans have been strengthened by adding new steel plates and replacing half a million original rivets with nearly twice as many high-strength bolts.

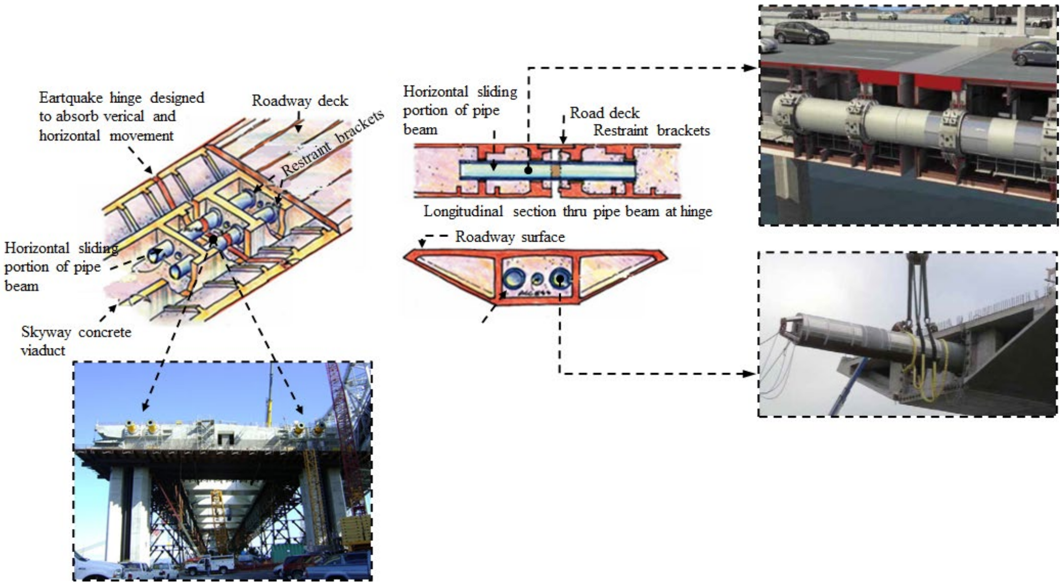

Figure 8. Details of seismic joint of the Oakland Bay Bridge.

The design of the new Oakland Bay Bridge prioritized seismic protection to ensure its long-term durability in the face of potential earthquakes [7][8]. The construction of the bridge incorporates numerous seismic isolators and connections with high ductility and ductile joints, allowing the structure to move during seismic events with minimal damage. Fig. 8 illustrates pipe beams connecting different segments of the bridge, capable of accommodating horizontal relative movement between sections. Additionally, in Fig. 9, ductile steel connections within the main bridge are depicted, further enhancing its seismic resilience. These features collectively contribute to the bridge's ability to withstand seismic forces and ensure its longevity [9][10]. The bridge was designed as a limited ductility structure with stable response to ground motions equivalent to the safety evaluation earthquake. The stability of the structure was demonstrated by means of pushover analysis or an equivalent method of structural evaluation [8, 9]. This means:

- The bridge shall have a clearly defined inelastic mechanism for response to lateral loads,
- Inelastic behavior was restricted to piers, tower shear links, and hinge pipe beam fuses,
- The detailing and requirement for full-ductility structures was met.

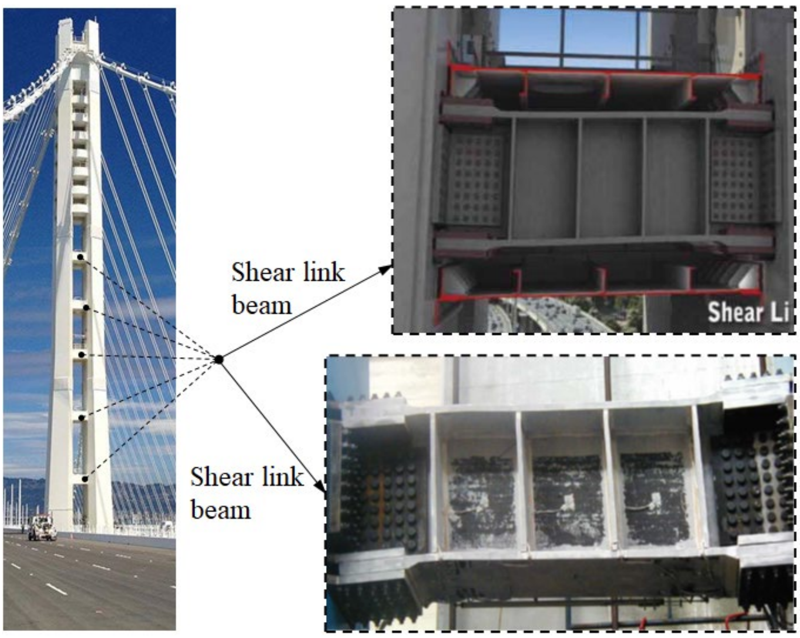

Figure 9. Tower shear link beams of the Oakland Bay Bridge.

5.4. PROPOSED BRIDGE LAYOUT VARIANTS

Six variants of the disposition of the bridge are foreseen. Those variants are:

- Reconstruction of the self-anchored suspension bridge,
- Self-anchored bridge with inclined cables and concrete tower,
- Single-pylon, asymmetric bridge with inclined cables,
- Single pylon, symmetrical bridge with inclined cables,
- Two-pylon, symmetrical bridge with inclined cables,
- Viaductal bridge.

VARIANT 1

According to the project, the construction consists of four basic phases, Fig. 10:

- Steel pylon construction,
- Construction of a steel orthotropic bridge structure on temporary pylons,
- Cabling and connecting the bridge structure to the cable using prestressed braces.

Figure 10. 1st proposed variant of the Oakland Bay Bridge.

VARIANT 2

The design for variant 2, Fig. 11 is very similar to variant 1, but what differentiates them is that the steel pylons have been replaced by concrete pylons. In order to support the concrete pylon, it is necessary to increase the dimension of the pylon's foundation, thus there are changes in the contract. In addition, the connection of the concrete pylon to the top of the piles, unlike the steel pylon currently in use, is more complex and would require redesign.

Figure 11. 2nd proposed variant of the Oakland Bay Bridge.

VARIANT 3

Variant 3 changes the bridge type from a suspension to a cable-stayed bridge with asymmetrical front and rear spans, Fig. 12. This variant provides an appearance similar to that of a suspended one and maintains a span of 385 meters of channel width.

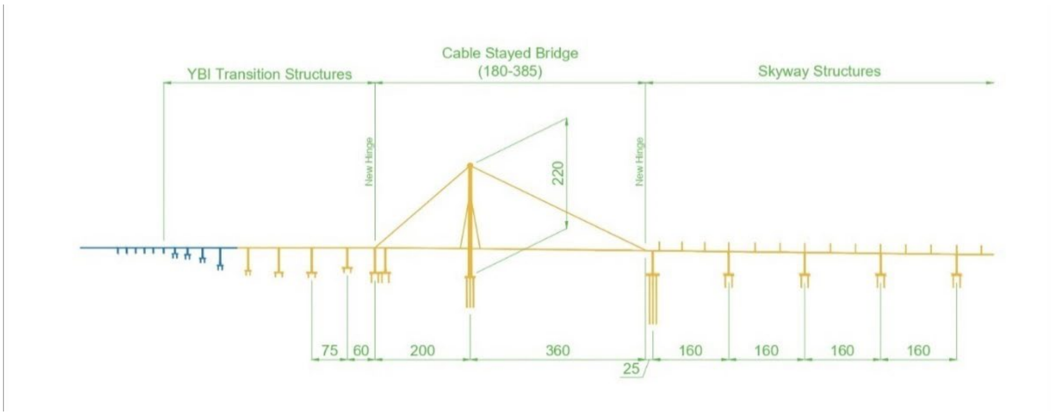

Figure 12. 3rd proposed variant of the Oakland Bay Bridge.

VARIANT 4

This variant changes the long-span bridge type from a suspension bridge to a cable-stayed bridge with symmetrical spans, Fig. 13. This approach allows for a suspension bridge-like appearance, but reduces the width of the canal span from 385 meters to 225 meters, in order to create symmetrical spans. The structural difference between the suspension variant and the cable-stayed variant includes the concrete pylon, which is the same height as the suspension bridge.

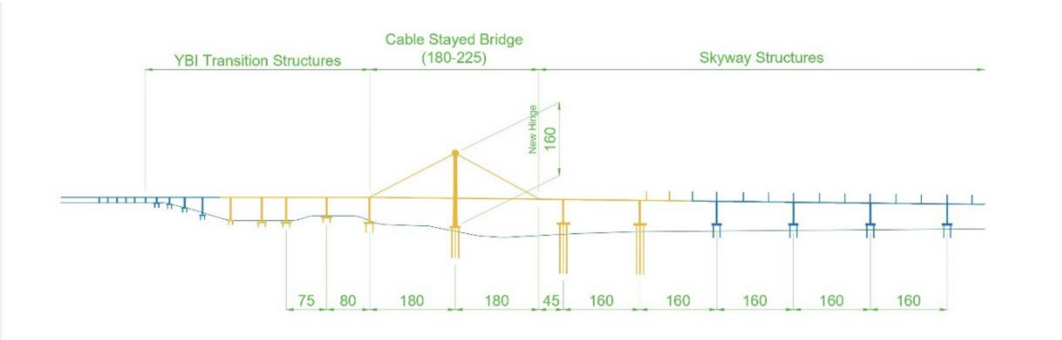

Figure 13. 4th proposed variant of the Oakland Bay Bridge.

VARIANT 5

This variant changes part of the bridge type from a single-pylon suspension bridge to a double-pylon bridge with inclined cables and symmetrical spans. This approach to the suspension bridge combines a symmetrical form with a clear channel width of 385 meters, Fig. 14.

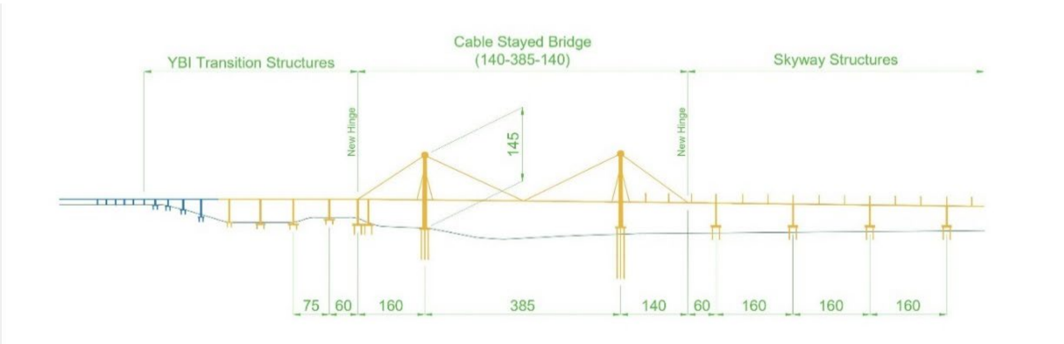

Figure 14. 5th proposed variant of the Oakland Bay Bridge.

VARIANT 6

This option would extend the existing road to Yerba Buena Island. This variant is not characterized by a span, but consists of a simple box girder design, which would present fewer challenges in bridge and structural design than other variants, Fig. 15.

Figure 15. 6th proposed variant of the Oakland Bay Bridge.

5.5. SELECTION AND DESIGN OF THE SUITABLE VARIANT

The Metropolitan Transportation Commission's proposal aimed to replace the existing two-story configuration with two parallel roads to improve seismic stability, construction efficiency, and aesthetics. It was started with the aim of eliminating the feeling of driving in a cage by placing eastbound passengers in the lower part of the cantilever and lattice structure. The plan called for ten lanes, with five on each side of the bridge, along with a space of 3 meters on each side. Due to the presence of deep silt layers in the eastern part of the bay, the new span had to be raised on shallow piles for 85 percent of its length, Fig. 16.

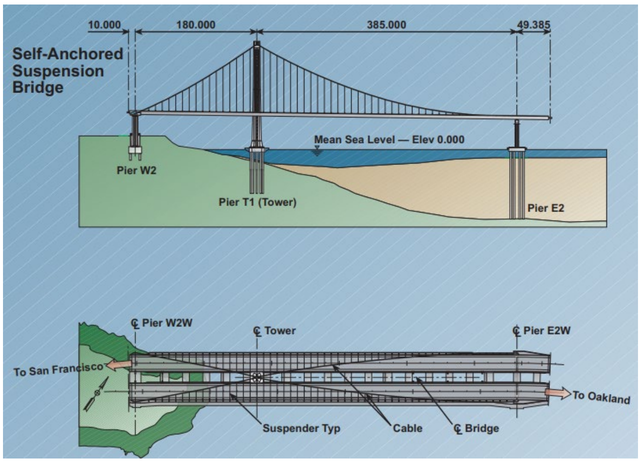

Figure 16. Cross section of Oakland Bay Bridge

In the end, the Design Task Force selected a self-anchored suspension bridge design, which became the longest single-pylon suspension bridge in the world. The final competition came down to self-anchored suspension span and cable span, Fig. 17.

Figure 17. Diagram of load transfer on the Oakland Bay Bridge.

To build a self-anchored suspension bridge, two actually have to be built, one as scaffolding to support the main form and the other, the actual bridge. In conventional suspension bridges, the pylons are built first, then the main cables are suspended between them and the bridge structure is attached to the cables. With a self-anchored suspension bridge, the process is reversed. Since the suspension cables are anchored to the bridge structure and not to the banks, at both ends of the bridge the bridge structure must be placed high above the water on a temporary structure [12]. The bridge needs truss scaffolding under the box girders for support. Also, scaffolding is needed to hold the bridge structure while it is being built. Then the cables that attach the bridge structure to the pylon are connected. Basically, two bridges are being built; a temporary structure is first built to support the roadway before the cables are installed, which is then removed.

The self-anchored form in which the cables are tied to the deck itself was necessary, because the geological conditions of the bay could not support anchoring in the very foundations of the bridge where the new East Crossing is located. As a result, a single suspension cable wraps over the tower and under the west end of the span, before wrapping again over the tower to anchor to both decks at the east end, Fig. 18 and 19. One cable is nearly 1.6 kilometers long, 8 meters wide, encircling the west end, before returning to the top of the tower to anchor at the east end. It is the longest suspension cable of any bridge in the world, with more than seventeen thousand 5 millimeter wires, each of which can support a weight of 3.5 tons [13].

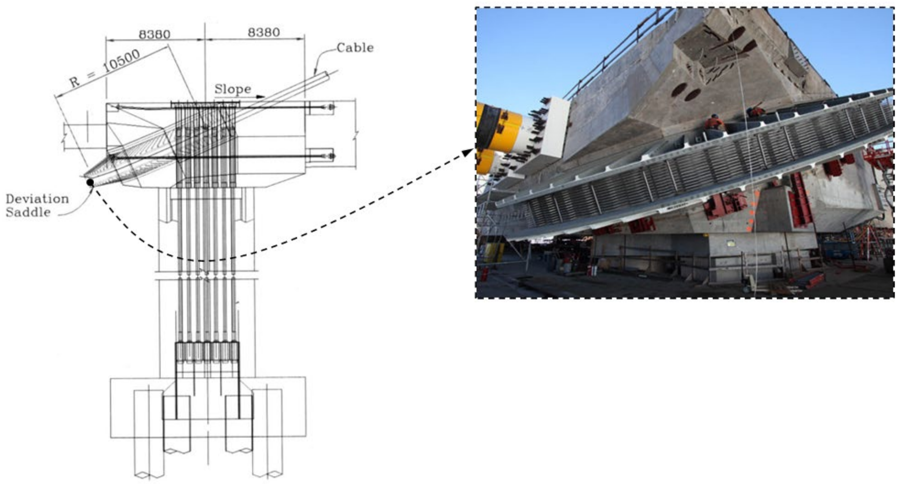

Figure 18. Detail of the saddle on the Oakland Bay Bridge.

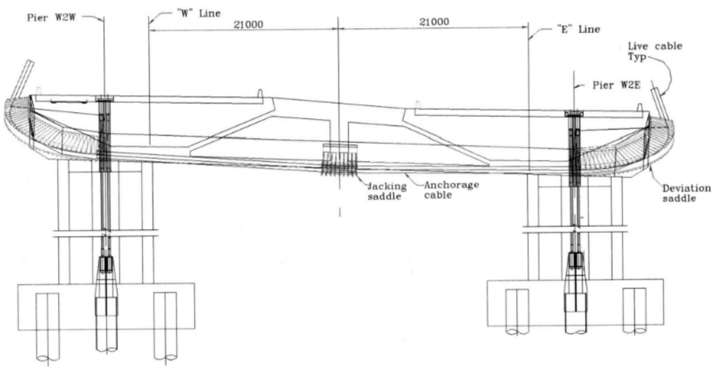

Figure 19. Cable anchorage loop.

5.6. BUILDING ISSUES

New concern was caused by the failure of the bridge in March 2013. Most of the large diameter bars were supposed to meet the A354BD standard, in various locations. All A354BD bars on the bridge are galvanized, as a form of corrosion protection. The second level of protection against corrosion includes: removal of humus from the substrate, use of stainless couplings, as well as protection with certain coatings.

The A354BD type rods[1] that were used and installed in 2008. The length of these bars is from 2.7 to 5.2 meters, Fig. 20.

On March 8, 2013, a few days after the bars were stressed, 9 nuts attached to the bars were observed to have lifted approximately 5 centimeters, indicating a break in the bars. After four days, twenty more queens were found in a similar condition. After this, the stress on the bars had to be reduced to 40% of the predicted intensity, in order to avoid further escalation of the situation. Three more bars subsequently failed, bringing the total number of failed bars to 32, in a 14-day period.

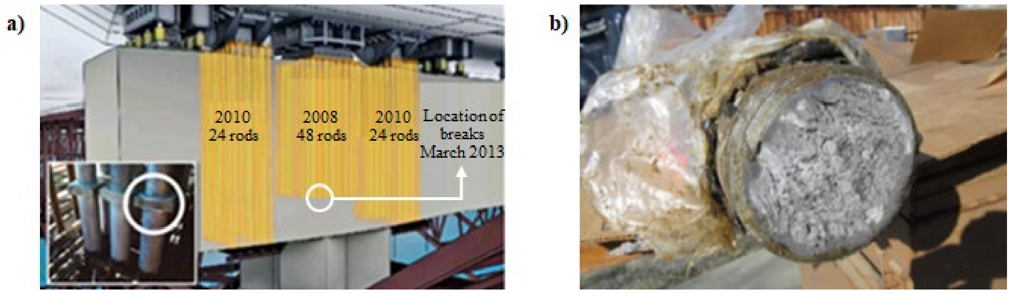

Figure 20. a) Schematic representation of the location of the rod failures; b) Appearance of the rod failures.

In order to investigate the cause of these fractures, a set of failed bar samples was taken for testing and analysis. Due to limited overhead clearance, the bars had to be gradually lifted and cut into 60-centimeter lengths for removal. Borescope inspection successfully photographed the lower surface of the fracture and unexpectedly revealed water and voids in the grout inside the cylinder at four out of five locations. Before completing the preliminary failure analysis, the design team made the decision to no longer rely on the remaining bars from 2008. As construction of the new design was scheduled for completion in December 2013, it was proposed to use shims to take advantage of the lateral load capacity bearings [12]. All A354BD bridge bars were identified and visually inspected again, except for the pylon foundation anchor bar. It was noted that, except for the pylon foundation anchor rod, all of the A354BD rods were supplied by the same manufacturer. Key differences between the failed 2008 bars and other bars on the bridge were identified. The 2008 rods were not subjected to magnetic particle (MT) testing on the threads, and were manufactured using a different process. In addition, a significant difference between the two groups of rods was their exposure to water. Construction photographs and a borescope examination revealed that the bottoms of the anchor rods from 2008, where the failures occurred, were exposed to standing water.

6. YAVUZ SULTAN SELIM BRIDGE

Since it was clear from the beginning that the bridge would become a symbol of the city, complex demands were presented in front of it:

- Considering that the location of the bridge is in close proximity to the Black Sea, it is necessary to ensure a navigational channel width of at least 1275 meters,
- The bridge should carry a load of up to four lanes in both directions, two railway tracks, as well as a pedestrian path on both sides of the bridge,
- The bridge should be constructed using a system of suspension bridges,
- Aesthetic conditions are of paramount importance when evaluating offers, and the bridge must not significantly deviate from the architecture of the existing two bridges over the Bosphorus,
- The bridge must be built in a short period of 36 months, plus 6 months for preparation.

The design confirmed structural efficiency and elegance. Compared to traditional suspension bridges, numerous advantages can be cited:

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[1] A354BD type rods – galvanized Ø7.62 cm (Ø3 in) rods that match the A354BD standard.

- Recognizable appearance of a suspension bridge,
- Despite heavy loads, a thin single-floor bridge structure of 5.5 meters in height was utilized, while the height of two-floor bridge structures ranges from 12 to 15 meters,
- Excellent aerodynamic shape of the structure,
- Good seismic behavior due to high damping and large rigidity,
- High limit state of serviceability with small deflections, which facilitate the functioning of the bridge,
- Good torsional properties due to high transverse stiffness caused by cross-linking cables,
- Construction process that saved time due to simultaneous construction of multiple bridge parts.

6.1. BRIDGE LAYOUT DESIGN

The bridge was designed by engineer Michel Virlogeux and architect Jean-François Klein, while the construction was carried out by a consortium of the Turkish company İçtaş and the Italian company Astaldi.

Compared to traditional suspension systems, the combination of a suspension bridge and a bridge with inclined cables should lead to material savings due to the following:

- The loads carried by inclined cables require less material than with suspension cables,
- A more rational pylon height can be used because the limitation regarding stiffness in the case of a suspension system does not apply to a combined system.

When choosing a combined bridge construction assembly, it must be taken into account that the bridge beams will have to endure significant axial forces. It will prove useful to introduce pressure into the bridge beam, in addition to the pylon, which prevents the installation of expansion joints at the pylon. Since the material requirement is lower for bridges with inclined cables than for suspension bridges, the angle of cable inclination can be minimized, and it can even be beneficial to carry all loads with a system of inclined cables, where it can be applied. This leads to the formation of a system quite similar to the Dischinger system.

The initial tender was released as part of a concession project. It required the design of a suspension bridge, with a main span of at least 1275 meters, whose appearance should resemble the two previously built bridges over the Bosphorus. To avoid building foundation pillars far from the shore, a solution was adopted that resulted in increasing the main span from 1275 to 1408 meters. The main obstacle of the project was an extremely tight time interval of 36 months allocated for the design and construction of the bridge. The hanging of the middle span of the bridge structure was accomplished using two rows of hangers, each anchored at a distance of 6 meters from the longitudinal axis of the bridge. Compared to the total width of the bridge of 58.5 meters, this is very small, leading to a tendency towards torsional twisting of the bridge beam. Additionally, great moving loads caused significant deflections.

BRIDGE BEARING SCHEME

On most pylons, the platform is supported on isolator pendulum bearings, which are not primarily used for seismic isolation but to reduce the longitudinal displacement of the platform and bending of the pylon under heavy rail traffic, with the aim of distributing the very large longitudinal load from rail traffic over more columns (avoiding excessive pylon bending). At the expansion joints at each end of the bridge section, sliding bearings are used to resist vertical loads, as rocking bearings would cause the face to lift during longitudinal movements, which would not be compatible with railroad tracks. Transverse forces (wind and seismic forces) are resisted by vertically oriented cup bearings on the abutment and pylon.

CONSTRUCTION

The Third Bosphorus Bridge, also known as Sultan Selim I Bridge, is made as a suspension bridge, but also has inclined cables, which are bound to cable-stayed bridges. The bridge is also a high-rigid suspension bridge. By adopting a suspended structural system in the middle of the main span and a brace system in the sections near the pylons, this bridge combines the advantages of a higher bridge for the possibility of a longer span and a cable-stayed bridge that exhibits greater stiffness, which is useful for railway traffic. The platform is divided into three zones depending on the type of support: suspended cables in the stiffening zone, supports and hangers from the main cables in the transition zone, and finally only hangers in the suspended zone.

BRIDGE ISSUES DURING THE DESIGN PHASE

Large forces and deflections are two very important problems, whose solution is found in the following:

- It is necessary to re-check the allowed stresses due to increased moving loads,
- Large cable deflections are not compatible with the design and geometry of the bridge beam.

The first problem is due to moving loads, which required the cables to be tensioned at very low constant stresses to avoid exceeding the limit states. This causes a decrease in cable stiffness due to increased deflection, which further increases the risk of harmful vibration effects.

Regarding the second problem, large deflections led to the displacement of cable anchor points to the maximum possible distance, Fig. 21. To avoid cable damage, the anchor pipe diameter had to be defined so that the cable could move freely without harmful contact. Increasing the anchor pipe diameter was only possible up to a size that would fit into the geometry of the bridge beam. The decision was made to create fixed points within the anchor pipe, i.e., to move the cable rotation point away from the anchor point, which was achieved using fixed deflectors.

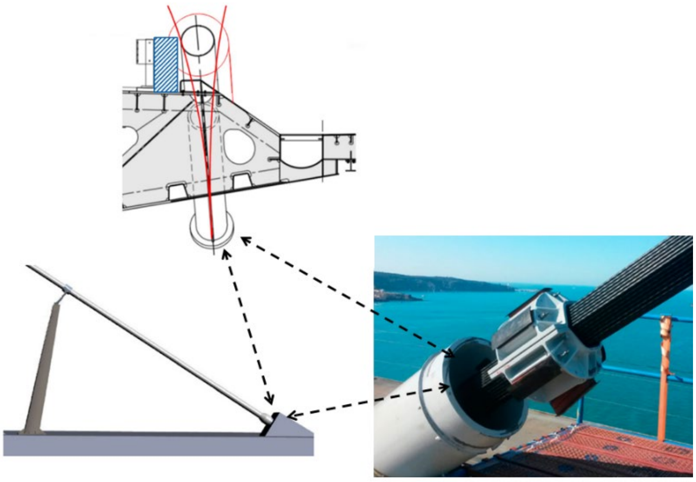

Figure 21. Representation of the location and method of cable anchoring.

6.2. ANCHORING BLOCKS

The anchoring blocks were excavated to a depth of almost 35 meters. The sides were supported by a stone wedge system and shotcrete concrete. 24,000 cubic meters of concrete, weighing 60,000 tons, was poured into each anchor block. The blocks stabilize the tension load caused by the main cables of the bridge. Both the Asian and European sides have anchorages with a capacity of 100,000 tons each. Together, the reinforced concrete and embankment, as a whole, have a constructive weight of each anchor block of approximately 150,000 tons. After the completion of concrete works, drainage, waterproofing and embankment works were carried out. Meanwhile, a concrete anchor block tensioned by 45,000 post-tensioning cables with a steel strength of up to 1,860 MPa was installed and the saddle distribution was ready.

6.3. BEARINGS

Pendulum isolators, also known as curved surface sliders, are a type of seismic isolation bearing. Other types include Lead Rubber Bearings (LRB) and High Damping Rubber Bearings (HDRB). Each of these types protects the supporting structures from sudden seismic ground accelerations – isolating the structure from the ground and thus significantly reducing the displacements/accelerations it is exposed to. Further key functions of seismic isolators generally include controlled dissipation of seismic energy and post-event re-centering (returning the supporting part of the structure back to its original location).

A typical isolation bearing has two spherically shaped sliding surfaces - the lower one, which enables rotation around any axis, and the upper one, which enables horizontal movements during an earthquake.

The main components are the same as a typical free-sliding spherical bearing, except that the upper sliding interface of the spherical bearing is flat, not curved, designed only to accommodate operating movements due to thermal expansion, etc, Fig. 22. The bed height increases as the upper plate (of varying thickness) moves from its central position during an earthquake. As a result, much of the work is done in raising the superstructure, thereby dissipating much of the earthquake's energy in a non-destructive manner.

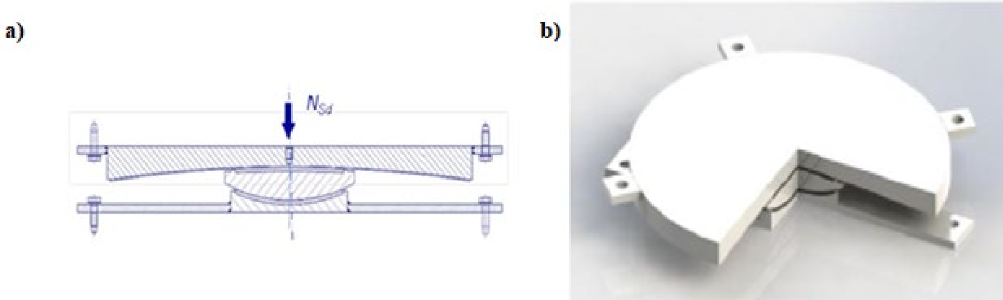

Figure 22. a) Schematic view of the spherical bearing of the bridge; b) Axonometric view of the spherical bearing of the bridge.

The dimensions of the pendulum bearing are primarily determined by two main parameters:

- The maximum load that can be carried, which defines the minimum area of the sliding surfaces.
- Movements that must be accommodated during operation or a seismic event.

For this construction, the following parameters were applied in the design of the largest bearings:

- Limit load power 125 MN;
- Displacement of the limit state of strength 764 mm.

The use of isolating pendulum bearings is an effective way of reducing the longitudinal movements of the suspension bridge pavement under live load, especially in the case of heavy rail traffic loads. However, if the radius of curvature of the main sliding surface of the designed bearing is low in relation to the vertical load to be supported, the design can become very inefficient and even impractical. In such cases, the spherical shape of the sliding surfaces of the bearing shell can be made cylindrical, Fig 23.

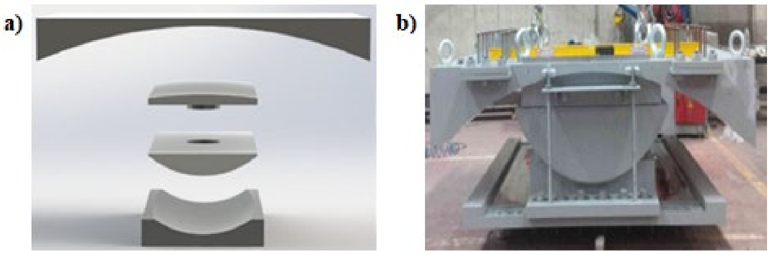

Figure 23. a) Schematic representation of the cylindrical bearing of the bridge; b) Appearance of the cylindrical bearing of the bridge.

6.4. BRIDGE PLATFORM

The bridge has an aerodynamic steel orthotropic bridge structure, which improves aerodynamic performance and aesthetic appearance in the main span. The spans on the shorter side are constructed using concrete that acts as a counterweight to the main span. The total length of the steel span is 1360 meters. It consists of prefabricated steel segments, each 58.5 meters wide and up to 24 meters long, Fig. 24. The steel segments are manufactured in parts, made up of 44 different panels. The bridge structure has 59 steel segments, the lightest of which is 300 tons, two segments exceed 450 tons, and the remaining 56 are 800 to 860 tons. The steel bridge segments were produced in three different places. The bridge segments were transported to the site by ship.

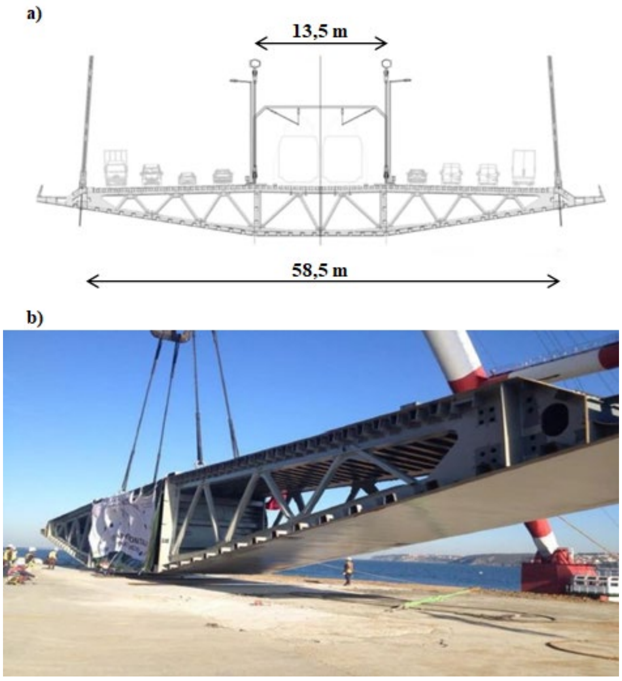

Figure 24. a) Cross-section of the Yavuz Sultan Selim Bridge's platform; b) Appearance of the Yavuz Sultan Selim Bridge's platform

6.5. PYLON

The pylons are A-shaped. Each pylon consists of two cylindrical reinforced concrete shafts underground and two triangular legs. The height of the pylon is 322 meters, which is a world record for a suspension bridge. The thickness of the concrete wall of 1.5 meters at the base is reduced to 1 meter at a height of 208 meters. The legs of the towers are interconnected, and the concrete transverse beam is located at a height of 61 meters, just below the level of the bridge structure. After their completion, a bridge structure was placed on it. The height of the supports between the pylons is 11 meters at the ends, and 6.5 meters in the middle.

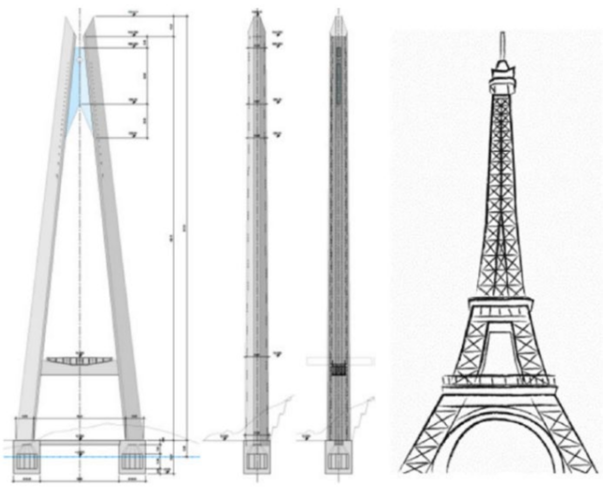

Figure 25. Pylon height comparison (Eiffel Tower and Yavuz Sultan Selim's pylon)

Anchor boxes for fixing the cables are placed in the pylons of the bridge from a height of 208 meters to 304 meters above sea level. There are a total of 176 anchor boxes in the four arms of the pylon bridge, i.e. 44 per leg. The heaviest of them weighs 65 tons.

6.6. CABLE

The mixed suspension system consists of three main parts:

- 176 holders (stiffeners) of cables,
- Hanging (main) cables with a length of 2420 meters,
- 34 pairs of vertical hangers, which support the central part of the span structure from hanging cables.

TENSIONING CABLES

176 stiffening cables were used, with lengths ranging from 154 to 597 meters and diameters between 225 and 315 millimeters. Each cable consists of 65 to 176 strands and each strand has 7 wires with a diameter of 5.2 millimeters. The strength of the wire is 1960 MPa. Each tower leg has 22 cables on the land side, which anchors 22 cables on the main span side.

One end of the stiffening cables is connected to the anchorages in the connecting pipes, which are located on the edges of the steel bridge segments, while the other end is connected to the anchor boxes in the pylons.

MAIN CABLES

Two main cables with a total weight of 12,882 tons were built, produced in a specialized factory in South Korea in less than a year. The main cables carry 34 steel segments, each weighing up to 860 tons. A total of 68 hangers weighing about 170 tons with a strength of 1860 MP. The main span cables have a diameter of 723 millimeters and consist of 113 strands. The main cable with a diameter of 752 millimeters and 122 strands extends from the side. Each strand has 127 galvanized wires with a diameter of 5.4 millimeters, which are arranged in a hexagonal pattern.

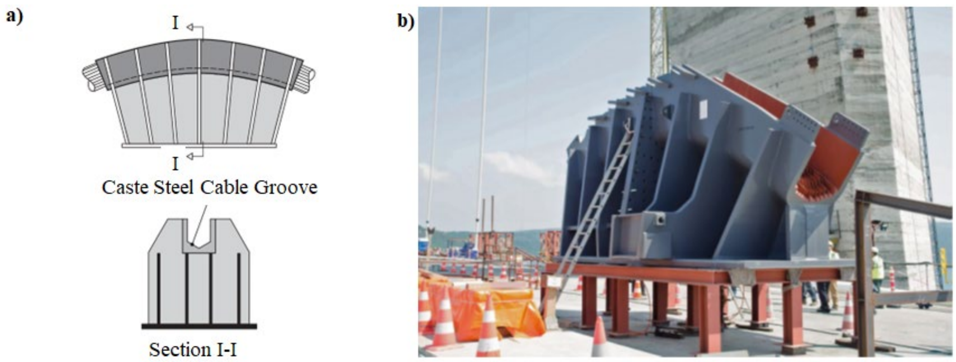

Figure 26. a) Schematic view of the saddle with a cast iron groove; b) Appearance of the saddle with a cast iron groove

Figure 27. Building process

HANGERS - PWS (PARALLEL WIRE SYSTEM)

Hangers are vertical cables that support the bridge structure by means of main cables in the transition zone and suspension zone. In the transition zone, 11 bridge deck segments are also supported by stiffening cables. In the suspended zone, the steel parts of the bridge are directly supported. The bridge contains a total of 68 hangers, length from 13 to 106 meters, diameter from 100 to 175 millimeters, total weight of 171 tons, strength of 1770 MPa.

7. DISCUSSION

This paper is written with an idea of analyzing and comparing, mainly, suspension bridges and cable-stayed bridges. The historical retrospective acknowledges different ideas and encountered problems that have occurred during design phase, as well as building phase.

Different aspects can be taken into account when we're talking about bridges and their purposes:

- Efficiency of solutions,
- Used materials,
- Economical aspect,
- Political aspect.

The main subjects of the paper, as mentioned earlier, are suspension bridges, as well as cable-stayed bridges. Different systems are used for different objectives, depending on many factors, such as soil mechanics, seismic activity, surrounding architecture etc. That's why, in the selection process, engineers encounter various obstacles.

When we talk about differences between girder bridges and cable supported bridges, main takeaways are:

- Girder beams need much more structural material to span the same distance as cable supported bridges.
- Main supporting points in girder bridges are located under the roadway, while main supporting points in cable supported bridges are located high above the roadway, on the pylon.
- In cable supported bridges, continuation of the main cables is required outside the main supporting points, so the tension in the cables can be transfered to the anchoring blocks on the ground.

From this comparison, the decisive advantage of cable supported bridges lays in the low consumption of structural material. Since this advantage only grows with span increase, it is obvious and only logical solution to use cable supported designs for greater spans.

As for the Oakland Bay Bridge, it is one of the modern marvels. The self-anchored suspension system was chosen over cable-stayed variants, as seen in the paper above. The main reason was the 385 meters wide chanel passage that had to be maintained, as well as inability to anchor the main cables, related to the bad geological conditions.

The Third Bosphorus Bridge encountered different obstacles, since it was provided very tight time window to execute all phases. The bearing system combines suspension bridge with the cable-stayed bridge, allowing for great spans and rigidity needed for railway bridges, respectfully to the mentioned types.

8. CONCLUSION

Today, suspension bridges represent one of the oldest and most common types of bridges. Bridges can be divided according to the type of construction, as well as according to the corresponding spans, so beam and arch bridges are more suitable for short spans, cable-stayed bridges for medium-long spans and suspension bridges for very long spans.

With the development of high-quality steels, which were used for the production of cables, the construction of bridges with inclined cables began to become more frequent. Cable-stayed bridges are usually anchored by themselves and thus create suitable solutions, especially in locations where the soil conditions are not favorable for foundations. An example of a cable-stayed bridge is the Sultan Selim I Bridge in Istanbul, Turkey. The need to stiffen the bridge by means of long, high-tension cables caused the creation of an entirely new construction method called the hybrid system, thus ushering in a new era of bridge construction. In addition to the new construction method, it is necessary to analyze the seismic resistance of this bridge, which is an extremely important feature, taking into account that the bridge is located in the seismic zone of the XI category, which is characterized by strong earthquakes. The solution was found in the use of bearings with dampers, which isolate the structure from a rigid connection with the ground, reducing movements. Two versions of bearings were used, spherical and cylindrical.

The suspension bridge construction system has developed and changed throughout history. Modern suspension bridges date from the 18th century. The choice of the span significantly affects the price of the bridge, and it is necessary to carefully approach the choice of the span, considering that the irrational dimensions of the span lead to unnecessary financial expenses. Suspension bridges can be anchored to the shore or to themselves, forming a self-anchored variant of the bridge. Self-anchored bridges are bridges that do not require additional horizontal anchoring, as is the case with cable-stayed bridges or girder bridges. The reconstruction of the San Francisco-Oakland Bay bridge is reflected in the replacement of the seismically vulnerable part of the bridge with a self-anchored variant of the suspension bridge. The need for reconstruction became apparent after the 1989 Loma Prieta earthquake, which highlighted the bridge's susceptibility to seismic action. During the design and construction, numerous challenges were overcome, such as maintaining the required width of the shipping channel, which caused the need for a larger span. The asymmetric variant with one pylon represents the optimal solution, which in itself represents an engineering challenge, considering that it is necessary to provide a balance of internal forces in each part of the bridge. Seismic impacts, which caused the collapse of the previous bridge, were suppressed by the installation of seismic dampers and a specific support system of the bridge structure.

The objective of this paper is to simplify the complex engineering hidden in the background of these critical objects, as well as to inspire engineers to take on the challenge of exploring different possibilities and solutions and to avoid designing boring and, in some cases, less efficient objects.

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